

# $K^+/\pi^+$ Probes of Jet Quenching in AA Collisions

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**Abstract.** Non-abelian energy loss in quark gluon plasma is shown to lead to novel hadron ratio suppression patterns in ultrarelativistic nuclear collisions. We apply recent (GLV) estimates for the gluon radiative energy loss, which increases linearly with the jet energy up to  $E < 20$  GeV and depends quadratically on the nuclear radius,  $R$ . The  $K^+/\pi^+$  ratio is found to be most sensitive to the initial density of the plasma.

Energy loss of high energy quark and gluon jets penetrating dense matter produced in ultrarelativistic heavy ion collisions leads to jet quenching and thus probes the quark-gluon plasma formed in those reactions [1, 2]. The non-abelian radiative energy loss,  $\Delta E(E, L)$ , suppresses the moderate  $2 - 3 \text{ GeV} < p_T < 10 - 15 \text{ GeV}$  distributions of hadrons in a way that can also influence the jet fragmentation pattern into different flavor hadrons. This is because quark and gluon jets suffer different energy losses proportional to their color Casimir factors (4/3, 3). First estimates [1, 2] suggested that  $\Delta E \approx 1 - 2 \text{ GeV}(L/\text{fm})$  would depend linearly on the plasma thickness,  $L$ , as in abelian electrodynamics. In BDMS [3] non-abelian (radiated gluon final state interaction) effects were shown to lead to a quadratic dependence on  $L$  with a much larger magnitude of  $\Delta E$ . The analysis of jet-quenching in  $Pb + Pb$  at  $\sqrt{s} = 20 \text{ AGeV}$ , however, indicated a negligible energy loss at that energy [4, 5]. In GLV [6, 7] finite kinematic constraints were found to reduce greatly the energy loss at moderate jet energies and we obtained  $\Delta E(E, L) \sim E \cdot (L/6 \text{ fm})^2$ . Here we apply the GLV energy loss to estimate more quantitatively the effect of jet quenching on the hadronic ratios at moderate  $p_\perp < 10 \text{ GeV}$  at the Relativistic Heavy Ion Collider (RHIC) energy,  $\sqrt{s} = 130 \text{ AGeV}$ . We illustrate the jet quenching effects for a generic plasma with an average screening scale  $\mu = 0.5 \text{ GeV}$ , strong coupling  $\alpha_s = 0.3$ , and an average gluon mean free path  $\lambda_g = 1 \text{ fm}$ . We introduce the opacity as the mean number of jet scatterings,  $\bar{n} = L/\lambda$ , which is assumed to be a finite number.

An advantage of looking into particle ratios is that uncertainties in the absolute normalization due to acceptance tend to cancel. The disadvantage is of course that high  $p_\perp$  particle identification is increasingly difficult. As we have shown in Ref. [8], the kinematically suppressed GLV energy loss turns out to depend approximately linearly on the jet energy,  $E$ . This linear dependence,  $\Delta E \propto E$ , leads to only a very weakly  $p_\perp$  dependent suppression of the transverse momentum distributions for the kinematic range accessible experimentally at RHIC. We focus on the  $p_\perp$  dependence

of the particle ratios in order to help pin down the jet quenching mechanism. Our primary candidate is the measurable  $K^+/\pi^+$  ratio.

In order to investigate the influence of the GLV energy-dependent radiative energy loss on hadron production, we apply a perturbative QCD (pQCD) based description of  $Au + Au$  collisions, including energy loss prior to hadronization. First, we check that the applied pQCD description reproduces data on pion and kaon production in  $p + p$  collision. Our results are based on a leading order (LO) pQCD analysis. Detailed discussion of the formalism is published elsewhere [9, 10].

Our pQCD calculations incorporate the parton transverse momentum (“intrinsic  $k_T$ ”) via a Gaussian transverse momentum distribution  $g(\vec{k}_T)$  (characterized by the width  $\langle k_T^2 \rangle$ ) [9, 10, 11] with the usual convolution of the parton distribution functions (PDF)  $f_{a/p}$ , partonic cross sections and fragmentation functions (FF)  $D_{h/c}$ , as:

$$E_h \frac{d\sigma_h^{pp}}{d^3p} = \sum_{abcd} \int dx_1 dx_2 dz_c d^2k_{T,a} d^2k_{T,b} g(\vec{k}_{T,a}) g(\vec{k}_{T,b}) \times \\ f_{a/p}(x_1, Q^2) f_{b/p}(x_2, Q^2) \frac{d\sigma}{dt} \frac{D_{h/c}(z_c, \hat{Q}^2)}{\pi z_c^2} \hat{s} \delta(\hat{s} + \hat{t} + \hat{u}). \quad (1)$$

Here we use LO PDF from the MRST98 parameterization [12] and a LO FF [13]. The applied scales are  $Q = p_c/2$  and  $\hat{Q} = p_T/2z_c$ .

Utilizing available high transverse-momentum ( $2 < p_T < 10$  GeV)  $p + p$  data on pion and kaon production at  $19 < \sqrt{s} < 63$  GeV we can determine the best fitting energy-dependent  $\langle k_T^2 \rangle$  parameter (see Ref. [9, 10] for further details on  $\langle k_T^2 \rangle$ ). One can conclude about the  $K^+/\pi^+$  ratio that, while agreement is reasonable for  $p_T \geq 4$  GeV, there is a systematic discrepancy at smaller transverse momenta. High statistics  $p + p$  data at RHIC will be essential to establish an accurate baseline to which  $A + A$  must be compared. Now we turn to the calculation for  $Au + Au$  collision at RHIC energy,  $\sqrt{s} = 130$  AGeV. As a first approximation, let us consider slab geometry, neglecting radial dependence. We include the isospin asymmetry and the nuclear modification (shadowing) into the nuclear PDF [14].

The value of the  $\langle k_T^2 \rangle$  of the transverse component of the PDF will be increased by multiscattering effects in  $A + A$  collisions. Two limiting cases were investigated with (i) a large number of rescatterings [11] and (ii) a small number of rescatterings (“saturated Cronin effect”) [9, 10]. Here we consider the influence of jet-quenching on the hadron spectra, leaving the inclusion of the multiscattering effect for future work. In this simplified calculation, jet quenching reduces the energy of the jet before fragmentation. We concentrate on  $y_{cm} = 0$ , where the jet transverse momentum before fragmentation is shifted by the energy loss,  $p_c^*(L/\lambda) = p_c - \Delta E(E, L)$ . This shifts the  $z_c$  parameter in the integrand to  $z_c^* = z_c/(1 - \Delta E/p_c)$ . The applied scale in the FF is similarly modified,  $\hat{Q} = p_T/2z_c^*$ , while for the elementary hard reaction the scale remains  $Q = p_c/2$ .

With these approximations the invariant cross section of hadron production in central  $A + A$  collision is given (in a somewhat abbreviated notation) by

$$E_h \frac{d\sigma_h^{AA}}{d^3p} = B \sum_{abcd} \int dx_1 dx_2 dz_c d^2k_{T,a} d^2k_{T,b} g(\vec{k}_{T,a}) g(\vec{k}_{T,b}) \times \\ f_{a/A} f_{b/A} \frac{d\sigma}{dt} \frac{z_c^*}{z_c} \frac{D_{h/c}(z_c^*, \hat{Q}^2)}{\pi z_c^2} \hat{s} \delta(\hat{s} + \hat{t} + \hat{u}). \quad (2)$$

where  $B = 2\pi \int_0^{b_{max}} b db T_{AA}(b)$  with  $b_{max} = 4.7$  fm for the 10 % most central  $Au+Au$  collision and  $T_{AA}(b)$  is the thickness function. The factor  $z_c^*/z_c$  appears because of the in-medium modification of the fragmentation function [15]. Thus, the invariant cross section (2) will depend on the average opacity or collision number,  $\bar{n} = L/\lambda_g$ .

We note that the GLV energy-dependent energy loss leads to a rather structureless downward shift of the single inclusive yields of all hadrons because  $\Delta E/E$  is approximately constant. This is in contrast to the results in [11], where an energy dependent fractional energy loss,  $\Delta E/E = (0.5 \text{ GeV}/E)(L/\text{fm})$ , was used.

More generally, the quenching factor depends also on fluctuations of energy loss that occurs because a single collision dominates the energy loss. We are presently testing the effect of fluctuations using the normalized  $f(\delta E) \propto \theta(\delta E - \delta E_0)/\delta E^2$  distribution of energy loss from [6] and  $\delta E_0$  fixed by  $\langle \delta E \rangle = \Delta E_{GLV}(E, L)$ . Preliminary results indicate, that fluctuations simply renormalize the effective opacity that is needed to obtain a fixed quenching factor. The reason that this simplification occurs in spite of the large effect of fluctuations is the approximate energy independence of the GLV *fractional* energy loss in the relevant jet energy range. Since other effects, such as expansion, also renormalize the value of the effective static opacity, we continue here to illustrate the effects of jet quenching simply varying  $L/\lambda_g$  as discussed above.

To understand the origin of the different dependence of the  $\pi$  and  $K$  quenching factors on  $L/\lambda_g$ , we consider the gluon contribution to the hadron yield for charged pions and kaons. For simplicity, we illustrate the gluon contribution to the non-quenched ratios only. Fig. 1. displays (top panel) the relative contribution of gluon fragmentation to the production of pions and kaons as a function of  $p_T$ . It can be seen that gluons dominate pion production while (valence) quarks dominate  $K^+$  production, especially at lower  $p_T$  values. Due to the dependence of jet energy loss on the color Casimir factor, pions will experience stronger suppression than kaons for the same value of  $\bar{n} = L/\lambda$ . There is a  $p_T$  dependence of this effect because the quark and gluon fragmentation functions differ. While  $\pi^+$  and  $\pi^-$  show an almost identical relation between quark and gluon fragmentation contribution, there is a difference between  $K^+$  and  $K^-$  in accordance with the different production mechanism of  $K^+$  and  $K^-$  [16]. Our main result is the prediction that there could be a factor of 2-3 enhancement in the  $K^+/\pi^+$  ratio in the  $p_T \sim 3 - 6$  GeV range for effective opacity  $\bar{n} = 4$ . The recently reported suppression of the  $\pi^0$  spectra in Ref. [17] corresponds to an effective static opacity in the range  $\bar{n} \approx 3 - 4$  [18].

In summary, we applied the GLV parton energy loss [6, 7] in LO pQCD to pion and kaon production in nuclear collisions. The energy dependence of  $\Delta E_{GLV}$  leads to a weak  $p_T$  dependent but *flavor dependent* quenching factor that increases with the effective opacity of the plasma. The enhancement of the  $K^+/\pi^+$  ratio in the  $2 < p_\perp < 10$  GeV range was found to be the most sensitive to the gluon opacity at RHIC energies.

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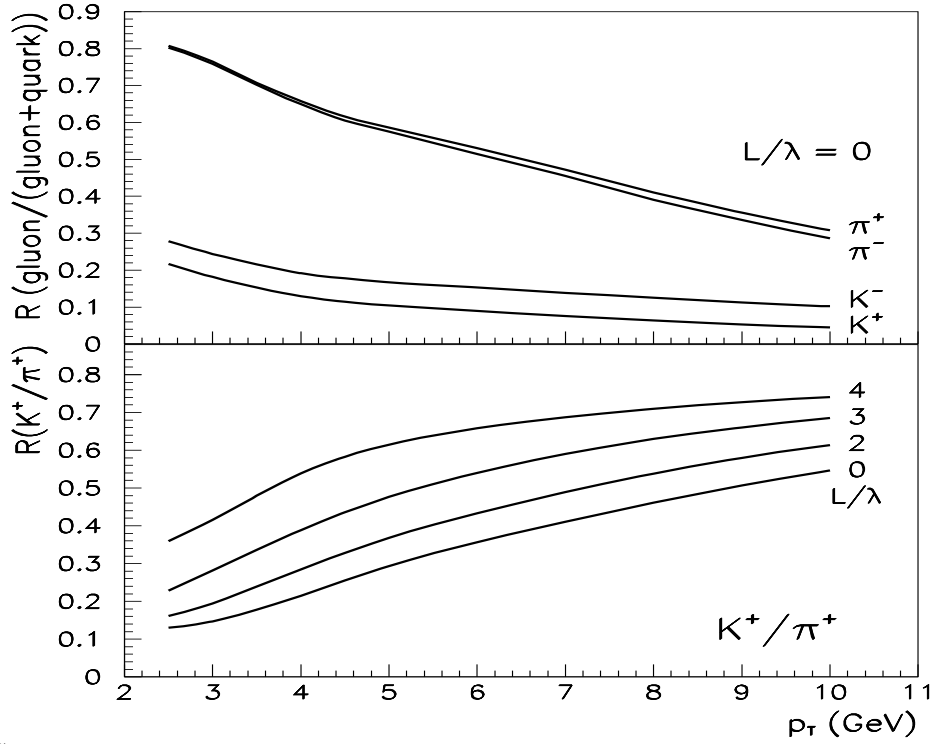


FIG. 1. Top panel: Relative contribution of gluon fragmentation to charged pion and kaon production at  $\sqrt{s} = 130$  AGeV without jet quenching. Bottom panel:  $K^+/\pi^+$  ratio in  $Au + Au \rightarrow h + X$  collision at  $\sqrt{s} = 130$  AGeV without jet-quenching ( $\bar{n} = 0$ ) and with it,  $\bar{n} = 2, 3, 4$ .

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